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RPPR Final Report

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Major Goals: Specifically, this project will enable the creation of a dedicated robotics lab for attracting students into STEM and providing real-world experience on the challenges and opportunities in the field. This robotics lab will enable, among many other things, research in the areas of physical human-robot interaction, mechatronics, artificial intelligence, web applications development, embedded systems development, and mechanical/electrical engineering. We believe that acquiring the proposed robotics equipment will greatly improve teaching capabilities at HT and accelerate research along many fronts including control, planning, and autonomous behaviors, and artificial intelligence. In particular, the proposed equipment and instrumentation will greatly facilitate ongoing research on physical human-robot interaction. Finally, the proposed equipment acquisition will catalyze further collaboration between HT and other leading institutions in the country including the University of Texas at Austin (UT).

Accomplishments: Huston Tillotson University was able to establish the Advanced Robotics Center (HT-ARC) that is the home of Robotics Lab. This lab was made possible through the grant award to acquire various equipment and instruments needed to design, experiment, and build robotics components, and to advance STEM education and research. In phase I of this grant, we furnished the Robotics Center with five (5) Actuator Testbeds each with a Control PC to simulate arm motion lifting (weight) control, and two (2) very powerful P170 (Taurus) Testbeds to simulate torso motion and control. We also established a lab for 3-D graphics design to model printable robotics components (shell) products with then print those components with the 3-D Printer. This lab also has five (5) computers each with 3-D software, and are networked through HP Server. Four (4) students enrolled in the course COSC4309 Computer Science Research/Project were the first cohort to be engaged in robotic research projects on the MTB Testbed at the Advanced Robotics Center.

The Phase II enabled us to contract the acquisition of Humanoid robotic test platform and associated tool kits and control computer. This system consists of multiple degrees of freedom for advanced robotics experimentation and control. This system will enhance and advance the knowledge gained in Phase I lab experiments. In an effort to further advance STEM Education and Research, the HT-ARC has established Modular Mobile Manipulator Robot lab that is used in the design, build Modular Mobile Manipulator Robots that can navigate obstacles while achieving its mission. The four (4) students who are currently enrolled in COSC4309 Computer Science Research/Project (fall 2017) were engaged in our robotics lab experiments on MTB Testbed, and will commence the assembly of a robotic arm to further their technical skills.

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The awarded grant has made it possible to establish a computer science concentration in Robotics within the Computer Science Degree Program. The Robotics Program as designed has been approved by the Computer Science Department, and the School of Business and Technology (SBT). It is now awaiting approval of university Educational Program Committee (EPC).

Students (4) who are currently in COSC4309 are currently finalizing their experimental research observations and findings/results based on experiments on MTB Testbed for Poster submission to the South Central Region Consortium for Computing Sciences in Colleges conference. (<http://www.ccsc.org/southcentral/submissions/studentinfo.html>). The deadline for submission is before April 2, 2018.

The HT-ARC as part of the computer science robotic curriculum also has developed the following robotics courses leading to computer science degree with a concentration in Robotics:

- COSCxxxx: Introduction to Robotics
- COSCXXX: Fundamentals of Technical Additive 3-D Graphics
- COSC2328:Robotics Motivation and Building
- COSC2329:Robotics Mobility/Autonomous/Agents/Robotics Intelligent
- COSC2330:Human-Robotic Interaction
- COSC4327:Robotics System Project

Two of our Computer faculty members are active engaged in maintaining and supervising students' activities off class lecture hours as they perform their individual experiments. The students (4) who are currently in the COSC4309 have positive responses to teaching, learning, and the use of the MTB Testbed, and use of other experimental equipment in the lab. The success of this project has opened up another opportunity for the HT-ARC to engage in a grant subcontract award to research the Exo-Skeleton Ergonomics and Degree of Freedom Movement for Apptronik Systems Inc. This research will involve two CS faculty members, and two (2) CS students.

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Training Opportunities: Four (4) students enrolled in the course COSC4309 Computer Science Research/Project were the first cohort to be engaged in robotic research projects at the Advanced Robotics Center. One of the major objectives is to attract and prepare additional minority students for degrees in STEM fields who would benefit from the increased innovation and new ideas in robot studies, design and development. Further objectives of this lab projects were to use and test robotic actuators (Motor Testbed (MTB) and P170 Taurus Testbed) (Figure 1a, 1b) developed and built by Appttronik Systems Inc. based on the Robotic curriculum developed for the robotic program in the computer science department. MTB is used to explore the fundamentals of electric motors and feedback control and Torque constant of an Electric Motor. And, the P170 Testbed is used to test the linkage equations that convert between actuator and robotic joint positions and also to perform more advanced control with position, velocity, and feed-forward terms.

Lab 1: Torque constant of an Electric Motor:

Explored the fundamentals of electric motors and feedback control using the Appttronik Motor Testbed (MTB) The objective is for students to calculate how much motor current is required to balance the weight. Since the weight of the load is measured (0.106Kg), and we know the distance of the weight from the pivot (0.144m), we can calculate how much torque is required to perfectly balance the weight. So the torque to balance the weight in this example is 0.15 Nm.

Lab 2. Measured Torque constant of an Electric Motor:

The purpose of this lab is to determine the motor's back-emf back electromagnetic force) constant by allowing the motor to accelerate to its maximum speed and then measuring the voltage applied to the motor.

Lab 3. Inertial Identification:

The purpose of this lab is to estimate the inertia of the motor based on frequency analysis. It also served as the introduction to feedback control

By completing Labs 1 and 2, students now have some confidence in the parameters of MTB motor. Most importantly, the type of control implemented is a validation of the motor's torque constant. Again, motor is treated as "torque source". A "torque source" is a device that can accurately produce a desired amount of torque.

Lab 4: Damping Identification:

The purpose of this lab is to refine the motor's viscous friction estimate based on temporal analysis of step signal tracking, and, also introduction to feedback control.

Motivation:

In the previous lab 3, system identification techniques to experimentally measure the inertia of an electric motor was used. However, the chirp signal caused the motor to hit its speed limit and therefore was not an accurate way of measuring damping present in the motor. In this lab, to measure the motor's damping without the use of a chirp signal, simple feedback controller was applied in the experiment.

Lab 5: Proportional-Derivative (PD) Control:

The purpose of this lab is to educate students on one of the most important types of feedback control: proportional-derivative control.

Feedback controller is implemented on the MTB Testbed and analyzed the closed-loop system's dynamic response to a step in desired position.

Therefore, this lab session will first establish a basic understanding of a mass-spring-damper before turning engaging the control of robotic actuators. The embedded code will move the motor from one position to another.

Lab 6: Feedback Linearization: The purpose of this lab is educate the students on how to transform the non-linear system into a linear one using a technique referred to as "Feedback Linearization" which works by choosing a torque input into the nonlinear system according to some specified rules and for the system to track some desired trajectory.

In previous labs we have studied systems with linear system characteristics. In this lab, the methods for controlling a non-linear system is examined, namely, one that is affected by gravity acting on an off-centered mass.

Running the lab:

Part A: Gravity Compensation:

In part A of this lab we explore the concept of linearizing our system by applying a control input that cancels out the system's natural dynamics (i.e. gravity). When we cancel out the dynamics due to gravity, we are left with a system that behaves as though it were unaffected by earth's gravity. Implementing this type of controller is often the first step in validating that we have successfully understood the system's natural dynamics through the following

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command:

```
roslaunch mtb_lab6_feedback_linearization gravity_compensation.launch
```

Part B: Gravity Inversion:

After demonstrating a control authority to nullify the system's non-linear dynamics, the next step is for to explore implementing new system dynamics for the system. In this part of the lab, a new control law that makes the MTB behave as though it were subjected to an inverted gravity situation is created using the following command:

```
roslaunch mtb_lab6_feedback_linearization gravity_inversion.launch
```

Part C: Impedance Control:

The final part of this lab implements what is commonly referred to as an "Impedance Controller". An impedance controller is simply a type of controller that make the system behave like some desired mechanical impedance (a mass-spring-damper for example). Students will recognize similarities between this impedance control law and the PD controller studied previously in Lab 5, and often times the two are interchangeable. The objective here is for our system to track some desired trajectory. It is accomplish by implementing an impedance control law that attaches a virtual spring and damper to a reference position of the actuator. Then, the control law cancels the system's natural dynamics and implements the desired mechanical impedance dynamics. Below is the command to run this part of the experiment.

```
roslaunch mtb_lab6_feedback_linearization impedance_control.launch
```

Students are advised to experiment with changing impedance control parameters and observe how the system responds.

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI

Participant: Azubike Okpalaeze

Person Months Worked: 12.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: Y

Other Collaborators:

Funding Support:

Participant Type: Co PD/PI

Participant: Abena Primo

Person Months Worked: 12.00

Project Contribution:

International Collaboration:

International Travel:

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Other Collaborators:

Funding Support:

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FINAL TECHNICAL REPORT

Grant#: W911NF-16-1-0431



**Next Generation Robots for Computer Science and STEM
Education,
and Research at Huston-Tillotson University (HT)**

**Azubike Okpalaeze, Ph.D.
Principal Investigator (PI)**

NOVEMBER 10, 2017

HUSTON TILLOTSON UNIVERSITY

900 Chicon Street - Austin, Texas 78702

Forward

It is with great honor and privilege the Huston Tillotson University, a Historically Black College and University (HBCU), the School of Business and Technology (SBT), and the Computer Science (CS) department seize this opportunity to thank the U.S. Army Research Laboratory (Army Research Office) for the resources to implement the project titled “Next Generation Robots for Computer Science and STEM Education, and Research at Huston-Tillotson University (HT)” award# W911NF-16-1-0431. Special thanks to the grant award officer, Mr. Kevin J. Bassler, and Mr. Joseph Myers. This opportunity has uniquely positioned the CS department to engage in collaborative robotics research engagements with neighboring institutions (UT-Austin, HBCU Universities, and Robotics High-Tech incubator companies) in Austin, Texas and beyond. It also furthers deep STEM Education and Research teachings that lead to rewarding career opportunities for our engaged STEM students who would become future contributors to robotic technology innovations and research, and advance the use of robots in the U.S. Army missions.

We also thank Dr. Luis Sentis of UT-Austin, Mr. Bill Welch and Dr. Nick Nicholas of Apptronik Systems Inc., and Dr. Joshua James of Additive Robotics for their technical training and supports. To Dr. Rhonda Moses (HT), Dr. Steven Edmond (SBT Dean), and the CS Faculty members, we thank you. And lastly, to our HT President & CEO, Dr. Colette Pierce Burnette, we thank you in a special way for your support and inspiration to forge ahead in the face of attendant challenges which now has metamorphosed into incredible opportunities for our students and faculty. We look forward to advance and maintain the Robotic Center as we engage in future technical research endeavors.

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Statement of the Problem Studied:

Specifically, this project founded a dedicated Advanced Robotic Center (Research lab) for attracting STEM students and provide real-world experience on the challenges and opportunities in the field of robotics. The robotics lab has enabled, among many other things, research in the areas of physical human-robot interaction, mechatronics, artificial intelligence, web applications development, embedded systems development, parallel programming, and mechanical/electrical engineering. In particular, the equipment and instrumentation have facilitated ongoing research on actuators leading to further studies of physical human-robot interaction. Finally, the equipment acquisition has catalyze further collaboration between HT and UT-Austin, Appttronik Systems Inc., and Additive Robotics, and it significantly advanced the computer science academic programs and degree offering. Four (4) students enrolled in the course COSC4309 Computer Science Research/Project were the first cohort to be engaged in robotic research projects and to pivot the lab experiments at the Advanced Robotics Center.

An actuator is a motor that converts energy into motion, which can also be used to apply force. It's typically a mechanical device that takes energy – usually energy that's created by air, electricity or liquid – and converts it into some kind of motion. That motion can be in virtually any form, such as blocking, clamping or ejecting, lifting, walking, and running. Actuators typically are used in manufacturing or industrial applications and might be used in devices such as motors, pumps, robots, switches and valves (Conjecture Corporation). There are four different types of actuators: hydraulic, pneumatic, electric, and mechanical. For the purpose of this project we concentrated on actuator for building and testing robots that will perform difficult tasks under morbid conditions. The two primary actuators were the Appttronik Motor Testbed (MTB) (Figure 1.), and the Appttronik P170 (Taurus) Testbed (Figure 2.). Testing requirements covered torque or force rating, long term holding, operational life, temperature performance, and sound testing for both pneumatic and electrical operators. And its adaptability in robotic design.

The type of actuators of interest is electric actuators. Electric actuators are devices powered by motors that convert electrical energy to mechanical torque. The electrical energy is used to create motion in equipment that require multi-turn valves like gate or globe valves. Electrical actuators are considered to be one of the cleanest and readily available forms of actuators. They are typically installed in engines, where they open and close different valves, and, also produce mechanical movement of robotics components parts (Anonymous),

Objectives of the Project:

Four (4) students enrolled in the course COSC4309 Computer Science Research/Project were the first cohort to be engaged in robotic research projects at the Advanced Robotics Center. One of the major objectives is to attract and prepare additional minority students for degrees in STEM fields who would benefit from the increased innovation and new ideas in robot studies, design and development. Further objectives of this lab projects were to use and test robotic actuators (Motor Testbed (MTB) and P170 Taurus Testbed) (Figure 1a, 1b) developed and built by Appttronik Systems Inc. based on the Robotic curriculum developed for the robotic program in the computer science department. MTB is used to explore the fundamentals of electric motors and feedback control and Torque constant of an Electric Motor. And, the P170 Testbed is used to test the linkage equations that convert between actuator and robotic joint positions and also to perform more advanced control with position, velocity, and feed-forward terms.

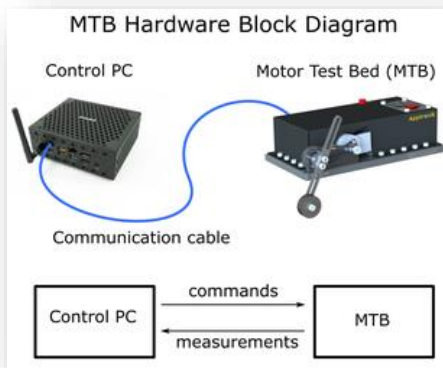


Figure 1a. MTB Testbed

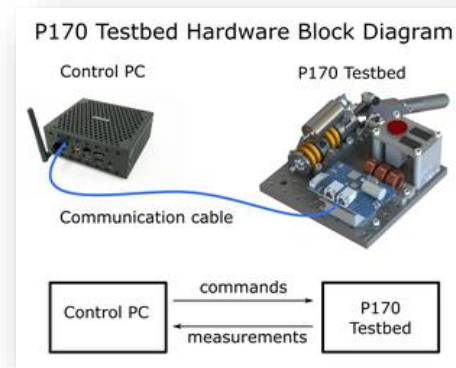


Figure 1b. P170 Testbed

Project Methodology:

1. **Motor Testbed:** In this lab we explored the fundamentals of electric motors and feedback control using the Apptronik Motor Testbed (MTB) (Figure 1a). The main components of the Motor Testbed are its Control PC and the Motor Testbed hardware.

Lab 1: Torque constant of an Electric Motor:

Explored the fundamentals of electric motors and feedback control using the Apptronik Motor Testbed (MTB) (Figure 1). (Kafader) (O. Stemme). The Lab experiment nomenclature is listed in Nomenclature page (Table 1.)

Objective:

The objective is for students to calculate how much motor current is required to balance the weight. Since the weight of the load is measured (0.106Kg), and we know the distance of the weight from the pivot (0.144m), we can calculate how much torque is required to perfectly balance the weight. So the torque to balance the weight in this example is 0.15 Nm. However, this amount of torque is being amplified by the belt driving the arm. The pulley ratio between the arm and the motor is 4:1. Therefore, the 0.15Nm of arm torque must be divided by 4 to obtain the motor torque necessary to balance the weight:

$$F_g = mg = 0.106Kg \times 9.81m/s^2 = 1.04N$$

$$\tau = F_g d = 1.04N \times 0.144m = 0.15Nm$$

of motor torque to balance the weight. This is our "ground truth" measurement.

Then, the lab1.cpp file is edited to apply different amounts of current until the value that perfectly balances the weight is found, and thus matches the amount of torque being applied to the arm. On this Testbed, 0.537A of motor current perfectly balanced the weight. A motor's torque constant is how much torque it produces per Amp of current applied to it. Since the load torque is measured and the motor current is tuned to balance the torque, both numbers are known:

$$k_\tau = \frac{\tau_{motor}}{I_{motor}} = \frac{0.037Nm}{0.537A} = 0.069Nm/A$$

The torque constant as provided by the datasheet is 0.0706 Nm/A for the MTB's motor (#339282): (http://www.maxonmotorusa.com/medias/sys_master/root/8821067677726/16-299-EN.pdf) From these two values, we can calculate our measurement error as follows:

$$\%_{error} = \left| \frac{experimental - theoretical}{theoretical} \right| \times 100$$

$$\%_{error} = \left| \frac{0.069 - 0.0706}{0.0706} \right| \times 100 = 2.27\%$$

2.27% error is very low indicating that the experiment to measure the torque constant is successful.

i. Motivation:

Electric motors are the building blocks of many important devices. Electric motors are at the heart of most electrically powered devices with moving parts including electric appliances, electric vehicles, and countless types of industrial equipment. They even cause the vibration in your cell phone. Not all of these devices require precise control of an electric motor though, which is one of the central topics in this lab guide. Precision control of electric motors is one of the key building blocks for automated machines and robotics engineering and development.

ii. Electric Motor Basics:

An electric motor is a device that converts electrical energy (current and voltage) into mechanical energy (torque and speed). Why and how electric motors work are questions were discussed brief in this lab. However, interested students may refer to the reference text for answers to such questions. This lab dealt only with the basic properties of electric motors which is sufficient knowledge to fully control their behavior. (Figure 2) shows the circuit model for an electric motor. When a voltage (V_{bus}) is applied to an electric motor, it produces current (i_m) based on the motor's electrical resistance (r), electrical inductance (l) and its back-emf voltage (V_m).

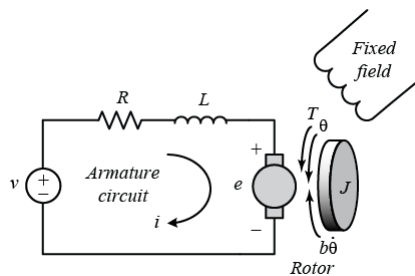


Figure 2. Circuit model of a Basic electric motor

iii. Torque Constant:

The focus was on the torque constant of an electric motor, which is denoted as k_t . Knowing the value of k_t is important because it gives a relation between the current passing through the motor and the amount of torque it produces ($\tau_m = k_t i_m$). It showed that motor torque is proportional to motor current, and the relationship between the two is given by the torque constant. Motors with larger values of k_{tau} produce more torque for a given amount of current.

iv. Speed Reduction and Torque Amplification:

Electric motors produce low amounts of torque and high amounts of speed, and high amount of torque at slow speed. For applications where high torque and low speed is required, a speed reduction mechanism must be used. A speed reducer acts like a lever, it reduces the motion and amplifies the force of one side and does the opposite to the other side (*figure 3*).

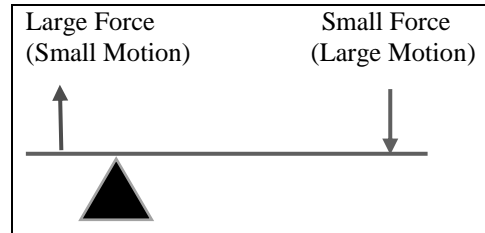


Figure 3. Lever Mechanics

If the speed ratio of a reduction mechanism is N , then the speed of the output (ω_o) is N times smaller than the motor's speed. ($\omega_o = \omega_m / N$). Conversely, the output torque (τ_o) is amplified. $\tau_o = \tau_m N \eta$. Here, η is the efficiency of the speed reduction mechanism. No speed reduction mechanism is perfect. Frictional loss inside the speed reduction mechanism reduces the available torque at the mechanisms output. In gear reduction mechanisms such as spur gears, worm gears, and planetary gears, this friction comes from the sliding of one gear tooth along another. As a result, the efficiency of a speed reduction mechanism must be represented in its torque amplification equation, and that representation is the value of η . A value of $\eta = 0.5$ means that a reducer is 50% efficient.

v. Experiment Measurement of the Torque Constant:

To implement a number of different types of control strategies on the MTB. An important first step is to validate the parameters of MTB system. The most basic control input in the MTB is the control over the motor's current. This is a common point of control for robotic systems for control simplicity and safety reasons. For later controller development, it will aide in knowing exactly how much torque MTB motor produces given an applied current, and how much torque is needed when a load (in lbs.) is applied. The motor manufacturer supplies the value of the motor's torque constant in its datasheet, but it is important to verify this value to ensure MTB system is configured correctly. To measure a motor's torque constant, there is a need to measure how much torque it produces. This measured value is often referred to as a "ground truth" value. A "ground truth" value is something that has been measured or calibrated with high confidence by direct observation rather than by inference. For example, a ground truth comparison for a thermometer would be to compare its measurement of boiling water at sea level to 100o C. Torque is equal force times distance, thus, a ground truth torque (τ_{gt}) can be obtained by applying a known force at a certain distance from the motor's point of rotation. One way to do this is fix an object of known mass at some known distance (d). For example, if an object is fixed with mass 0.1 Kg at 0.1 m from the point of rotation, the object would apply a force due to gravity of

$g = mg = 0.1 \text{ kg} * 9.8_{ms^{-2}} = 0.98$, therefore, a torque of $\tau_{gt} = F_{gd} = 0.98N * 0.1m = 0.098N_m$. Potential sources of error in the value of torque applied are error in distance from the pivot, mass measurement by a scale, gravitational acceleration due to altitude and latitude on the surface of the earth. (*Figure 4.*)

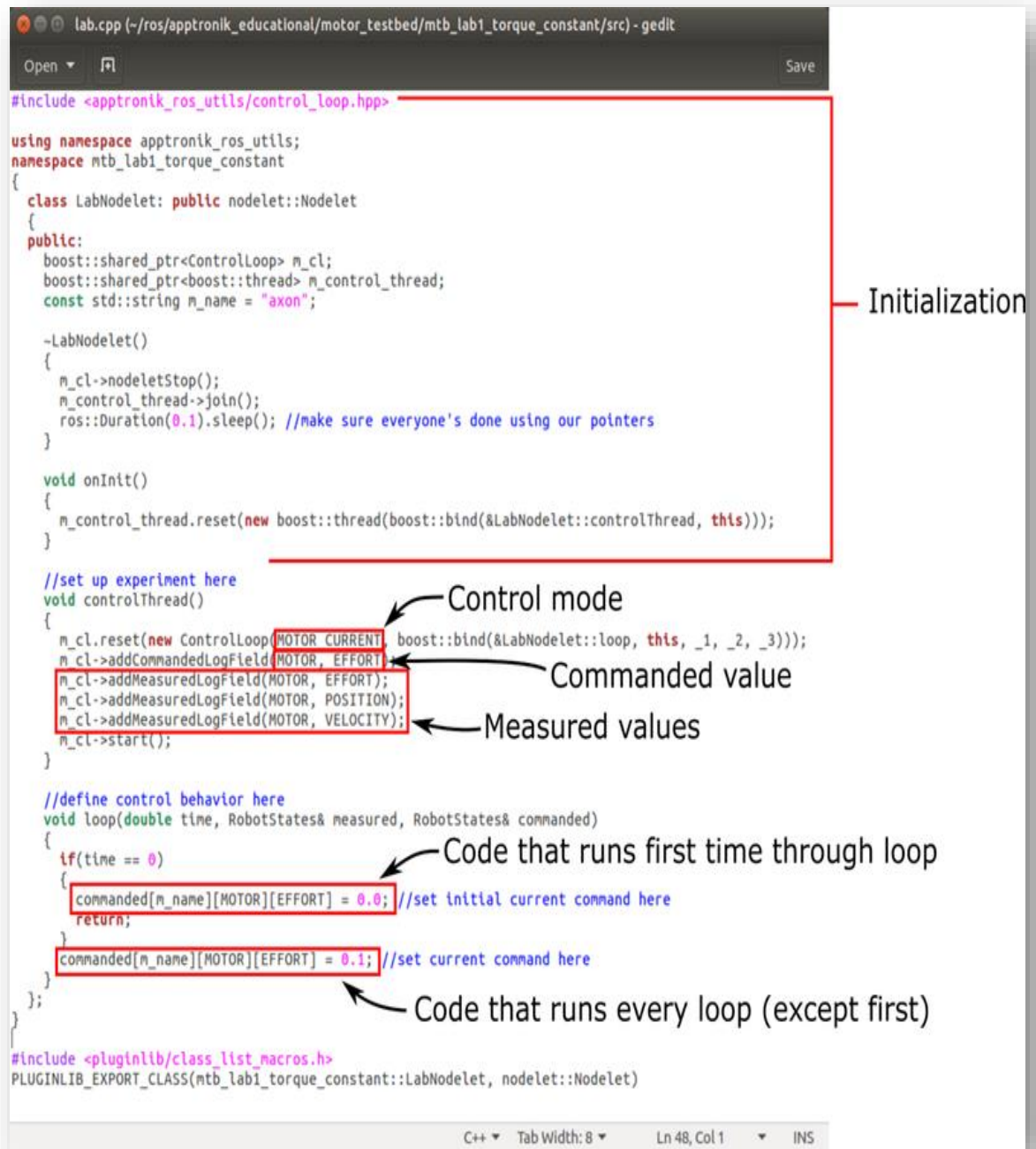
Code Structure:

Figure 4. Sample Code for Lab 1.

b. **Lab 2. Measured Torque constant of an Electric Motor:**

The purpose of this lab is to determine the motor's back-emf back electromagnetic force) constant by allowing the motor to accelerate to its maximum speed and then measuring the voltage applied to the motor. (Kafader) (O. Stemme)

Part of this circuit model is a voltage that the motor generates as a result of its motion. Similar to how the motor's torque is proportional to the current flowing through the motor, a motor's back electromotive force, or just back-EMF, is the voltage produced across the motor and is proportional to the motor's speed (Figure 5.) (Kafader) (Stemme)

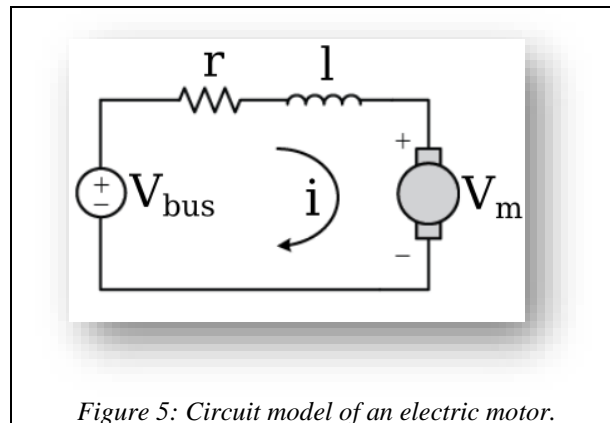


Figure 5: Circuit model of an electric motor.

Experimental Measurement of the Speed Constant:

To measure the MTB's speed constant, voltage is applied to the motor to measure its speed. Because the MTB uses a current controlled driver voltage is applied to the motor indirectly. One way to do this is to apply a large amount of current to the motor while it is unloaded and free to spin. This way, the motor driver accelerates the motor to the point where the back-EMF voltage is the same as the supply voltage (V_{bus}). When the motor reaches its no-load speed, the supply voltage measured and the motor's back-EMF voltage is obtained. Measurement of the motor's speed is accomplished with the use of a quadrature encoder that is integrated within the motor's assembly. The embedded controller within the MTB reads this encoder and differentiates the signal to obtain a measurement of the motor's velocity (Figure 6.).

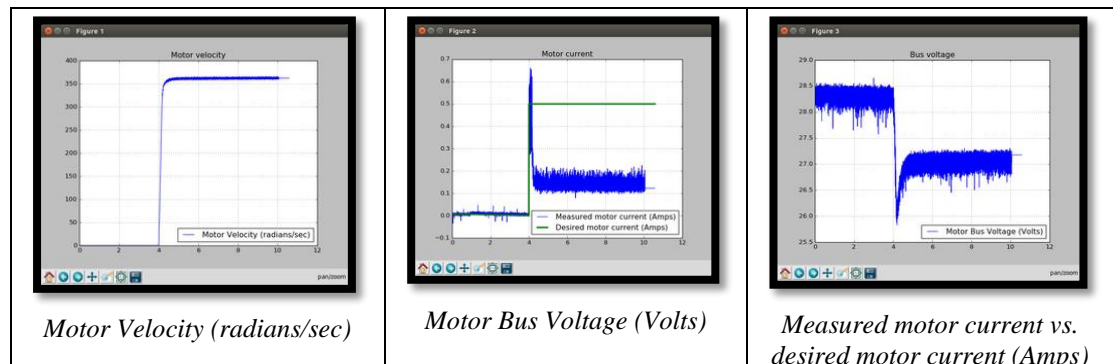


Figure 6. Motor Velocity vs. Time – Control Behavior

c. **Lab 3. Inertial Identification:**

The purpose of this lab is to estimate the inertia of the motor based on frequency analysis. It also served as the introduction to feedback control (Bélanger).

By completing Labs 1 and 2, students now have some confidence in the parameters of MTB motor. Most importantly, the type of control implemented is a validation of the motor's torque constant. Again, motor is treated as "torque source". A "torque source" is a device that can accurately produce a desired amount of torque. In reality, MTB motor current can be controlled, and, the measured relationship between current and torque has been established in Lab 1. Thus, it is possible to electively command the motor's torque as well. This knowledge of the motor's torque output is further used in the next two labs to identify further parameters of the MTB Testbed. Identifying the parameters of MTB system are important steps towards creating controllers for it. (Figure 7, & 8.)

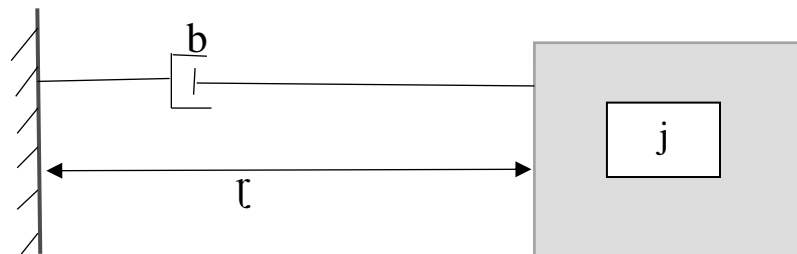


Figure 7. Inertia-damper Model



Figure 8. Sample model of an electric motor

To move something with inertia, a force must be applied to the inertia. To develop controllers that can move the inertia of the motor to a certain position helps to know the value of the inertia (how "heavy" it is). In this lab, we identify the inertia of the motor and the transfer of control (resistive force/torque) of a mass or inertia must be proportional to its acceleration. The system's transfer function can be measured by providing an excitation signal to the motor's current at a number of different frequencies and recording the resultant velocity. A good way to do this is to apply a chirp signal as the desired motor current. A chirp signal is a sine wave whose frequency increases with time (Figure 9).

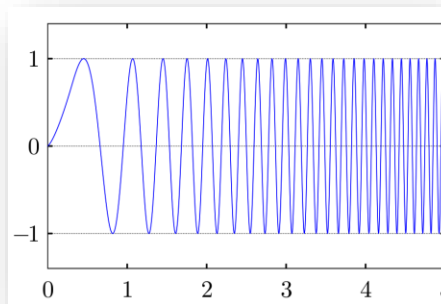


Figure 9. Chirp Signal

To identify the motor's model parameters use the "sys_id.py" script. The goal here is to identify values for inertia, j . The script requires four command line parameters to run:

- Data log file name
- Torque constant (measured in Lab 1)
- Guess for inertia value (students should find this value)
- Guess for damping value (this value will be identified in the next lab)

For example command code:

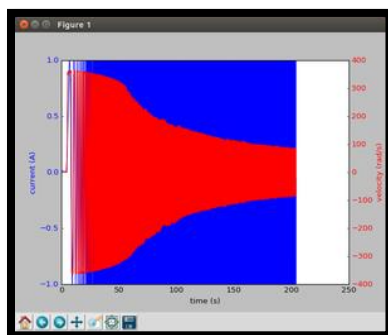
```
roscd mtb_lab3_system_id_inertia
```

```
python src/inertia_id.py /home/apprtronik/log/log_20170215T193618.csv 0.069 0.000023 0.00005
```

(Figure 10).

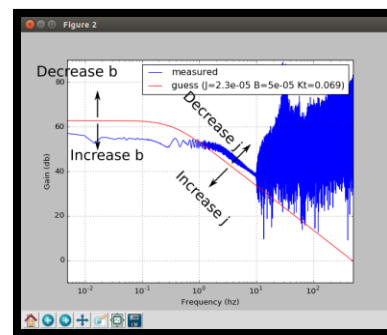
So with the above command the parameters are:

- Log file: /home/apprtronik/log/log_20170215T193618.csv
- Torque constant: 0.069 Nm/A
- Inertia: 0.000023 kg*m²
- Damping: 0.00005 Nm/rad/s



This graph visualizes the data collected from the experiment

**** Figure 10. Python Script for Data Collection and discovering vales of j and b**



This graph is the plot we will use to discover the values of j and b :

**** Remember, this chirp response does not produce accurate values for the b parameter. The reason for this is because at low frequencies of the chirp, the motor reaches its no-load speed which is a saturation behavior. This saturation creates a non-linear response to the applied current and the transfer function is a model of a linear system.**

d. **Lab 4: Damping Identification:**

The purpose of this lab is to refine the motor's viscous friction estimate based on temporal analysis of step signal tracking, and, also introduction to feedback control. (Bélanger)

Motivation:

In the previous lab 3, system identification techniques to experimentally measure the inertia of an electric motor was used. However, the chirp signal caused the motor to hit its speed limit and therefore was not an accurate way of measuring damping present in the motor. In this lab, to measure the motor's damping without the use of a chirp signal, simple feedback controller was applied in the experiment. (Figure 11)

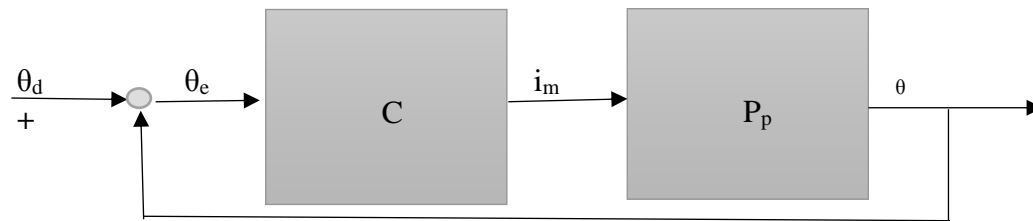


Figure 11: Diagram of a basic feedback controller

Note that in the feedback controller, P_p is the physical system we want to control. Typically the control objective is to use the feedback controller to make θ track its desired value, θ_d . However, perfect tracking is not the objective in this lab. Instead, we will analyze the response of the system to a change in the desired value (θ_d) and compare this response with an ideal, simulated response. C in the feedback controller is called a compensator, and is typically implemented in software. It is used to make the system as a whole behave in some desired manner. With one basic rule, we can create an equation that describes the behavior of the feedback controller. Namely, that the output of a transfer function equals the input times the transfer function itself. This comes from the basic definition of a transfer function where the transfer function P has the relationship with its input H_{in} and output H_{out} Functions.

For the purposes of this lab we will use a simple form of feedback called proportional feedback. In this control scheme, we define C to simply be a constant, K_p in this case. This type of controller applies more effort to the plant (P_p) the further away the measured value is from the desired value. If we substitute this value for C and the full definition of P_p we get the representation of the close loop transfer function.

To identify the motor's damping parameters, use the "*damping_id.py*" script. The goal here is to identify values for damping b . The script requires five command line parameters to run:

- Data log file name
- Torque constant (measured in Lab 1)
- Inertia value (measured in Lab 3)
- Guess for damping value (students should find this value)
- Feedback gain (the " k_p " value used in Lab4.cpp)

For example (*command code*):

```
roscd mtb_lab4_system_id_damping
python src/damping_id.py /home/apprtronik/log/log_20170315T152833.csv 0.069
0.000014 0.00003 0.05 (Figure 12)
```

So with the above command the parameters are:

- Log file: /home/apprtronik/log/log_20170315T152833.csv
- Torque constant: 0.069 Nm/A
- Inertia: 0.000014 kg*m²
- Damping: 0.00003 Nm/rad/s
- Feedback gain: 0.05

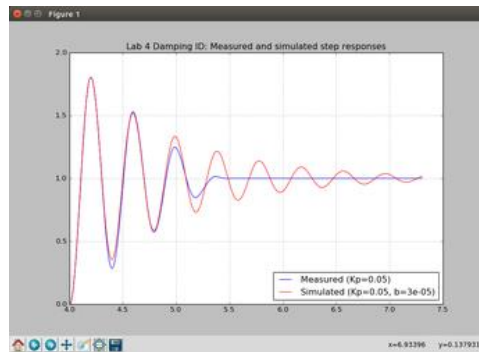


Figure 12. Simulated measured line to measured data

**The blue and red lines have been tuned so that the first peak of each curve is close to the same value. This is what the students should aim for. The red line is fine-tuned to simulated line by changing the value of damping in the python script above (its value is 0.00003 as *figure 11*). Since the simulated line matches the measured line, it is determined that the value of 0.00003 is a good fit to the measured data. The intent is to simulate what happened in the real system.

e. **Lab 5: Proportional-Derivative (PD) Control:**

The purpose of this lab is to educate students on one of the most important types of feedback control: proportional-derivative control. (Tedrake)

Feedback controller is implemented on the MTB Testbed and analyzed the closed-loop system's dynamic response to a step in desired position. The system's response, shown in *Figure 13 & 14*, closely resembles that of a more generic type of physical system: a mass-spring-damper. Because of this similarity, it is extremely helpful for robotics and other control engineers to become familiar with the behavior of mass-spring-damper systems. The physical laws that govern the dynamics of a mass-spring-damper system are found in many other physical systems including electrical, mechanical, and fluid systems. Therefore, this lab session will first establish a basic understanding of a mass-spring-damper before turning engaging the control of robotic actuators. The embedded code will move the motor from one position to another. A PD controller has two different parameters: a proportional gain (K_p) and a derivative gain (K_d). The K_p gain is analogous to a spring (higher values make the motor appear "stiffer" to disturbances) while the K_d gain is analogous to a damper (higher values make the motor appear more damped). The following line determines how long the program will run before saving data to a log file: `m_cl->start(5.0);`

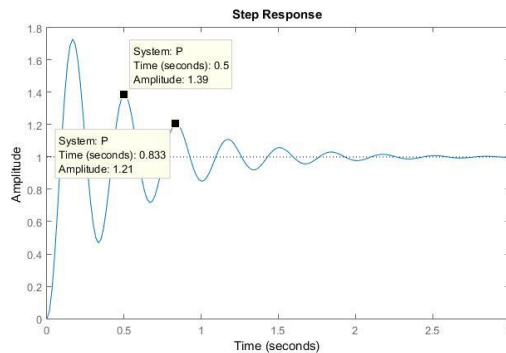


Figure 13: Natural frequency of a mass-spring-damper system

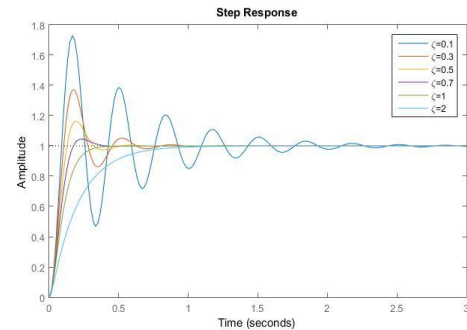


Figure 14: Change of damping ratio in a mass-spring-damper system

Student is encouraged to increase this run time and to push on the MTB's arm output to feel what the PD controller feels like.

- How does it feel with $K_d = 0$? $K_p = 0$?
- How do you tune K_p and K_d to create a critically damped system?
- How do you tune K_p and K_d to obtain a certain system bandwidth?

These are all exercises that can be carried out in this portion of the lab. To compare the experimental step response with our simulated model of the system we can use the following python script:

```
roscd mtb_lab5_pd_control
python src/pd_step_viz.py /home/apprtronik/log/log_20170316T160242.csv
0.069 0.000014 0.00003 0.2 0.01
```

The python script's parameters are as follows:

1. Data log file name
2. Torque constant (measured in Lab 1)
3. Inertia value (measured in Lab 3)
4. Damping value (measured in Lab 4)
5. Proportional feedback gain (the " K_p " value used in lab5_step.cpp)
6. Derivative feedback gain (the " K_d " value used in lab5_step.cpp)

The motor will attempt to track the sinusoidal trajectory given the PD parameters (K_p and K_d) provided. In addition, a running total of error per unit time (desired position - measured position) is displayed on the screen.

- What happens to this error when you block the motion of the arm (thus creating a system disturbance)?
- What happens to this error when you add mass to the arm?
- What happens to the error when you change the K_p and K_d gains?
- How does the arm feel when higher or lower K_p and K_d gains are used?
- What are the maximum K_p and K_d gains you can use and what limits their magnitude.

The control mode parameter sets the mode in which the embedded "Axon" controller operates. Possible options include the following.

Mode	Command Value	Meaning
MOTOR_CURRENT	(MOTOR, EFFORT)	Send desired motor currents to the embedded controller. Assume accurate current tracking is accomplished.
MOTOR_POSITION	(MOTOR, POSITION)	Send desired motor position to the embedded controller. A PID controller is implemented on the embedded controller to track motor position.
ACTUATOR_FORCE	(ACTUATOR, EFFORT)	Send desired actuator force to the embedded controller. A feedback controller is implemented on the embedded controller to track actuator force.
ACTUATOR_POSITION	(ACTUATOR, POSITION)	Not yet implemented.
ACTUATOR_VELOCITY	(ACTUATOR, VELOCITY)	Not yet implemented.
ACTUATOR_IMPEDANCE	(ACTUATOR, EFFORT)	Send desired actuator force, position, and velocity to the embedded controller. A PD controller's output is added to the actuator effort term and fed to an embedded force controller.
	(ACTUATOR, POSITION)	
	(ACTUATOR, VELOCITY)	

**** Table 1. Control Mode Parameter set**

*** This field in the code is coupled to the Control Mode. See the above table for the proper pairings of Control Modes and Commanded Values

Measured data can be added using the functions below. Components are: MOTOR, ACTUATOR, JOINT. State types are: POSITION, VELOCITY, EFFORT.

```
m_cl->addCommandedLogField([component], [state_type]);
m_cl->addMeasuredLogField([component], [state_type]);
```

- f. **Lab 6: Feedback Linearization:** The purpose of this lab is educate the students on how to transform the non-linear system into a linear one using a technique referred to as “Feedback Linearization” which works by choosing a torque input into the nonlinear system according to some specified rules and for the system to track some desired trajectory.

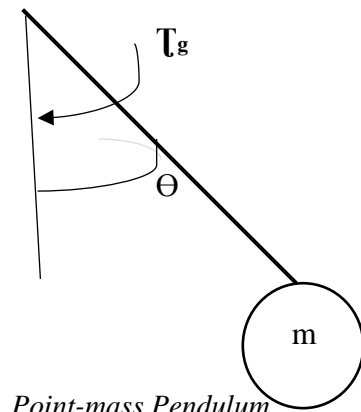
In previous labs we have studied systems with linear system characteristics. In this lab, the methods for controlling a non-linear system is examined, namely, one that is affected by gravity acting on an off-centered mass.

Hardware configuration:

Mount 8 washers onto the load arm and configure the load arm such that it is attached to the pulley at one end (Figure 15).



Figure 15. MTB Testbed with loaded arm



Point-mass Pendulum

**** WARNING:** In this configuration the MTB can dangerously swing the heavy weight at high velocity. Please ensure that the MTB is firmly mounted to a secure surface and that the area around the MTB is clear. Additionally, always be prepared to hit the red "Emergency Stop" button if code does not behave as expected. It is recommended to end each lab by hitting the E-stop before ending the code with Ctrl+C.

Always note that the motor's "zero" position is determined based on the position of the motor when the MTB's logic power is turned on. For this lab to work correctly, the motor's zero position must correlate to the arm being vertically oriented with the weight at its lowest position.

We can derive the torque acting on the pendulum due to gravity by first considering the definition of torque; Torque equals force times distance: (Table 4.Nomenclature)

$$\tau = Fd.$$

In the case of the pendulum, the force is the force due to gravity acting on the point mass:

$$F = -mg.$$

The force is negative because it is creating a torque in the clockwise direction and we define positive torque to be in the counter-clockwise direction. The distance at which this force is acting from the pivot point is the projection of the length of the pendulum in the direction of gravity: (Table 4.Nomenclature)

$$d = l \sin \theta_a.$$

Running the lab:

Part A: Gravity Compensation:

In part A of this lab we explore the concept of linearizing our system by applying a control input that cancels out the system's natural dynamics (i.e. gravity). When we cancel out the dynamics due to gravity, we are left with a system that behaves as though it were unaffected by earth's gravity. Implementing this type of controller is often the first step in validating that we have successfully understood the system's natural dynamics.

```
roslaunch mtb_lab6_feedback_linearization gravity_compensation.launch
```

Part B: Gravity Inversion:

After demonstrating a control authority to nullify the system's non-linear dynamics, the next step is for to explore implementing new system dynamics for the system. In this part of the lab, a new control law that makes the MTB behave as though it were subjected to an inverted gravity situation is created using the following command:

```
roslaunch mtb_lab6_feedback_linearization gravity_inversion.launch
```

Gravity inversion is just one example of new dynamics we can impose on our system. Other dynamics are possible. For example, can you make the MTB behave as though it were subjected to gravity from the left? Can you add damping to the system as well?

Part C: Impedance Control:

The final part of this lab implements what is commonly referred to as an "Impedance Controller". An impedance controller is simply a type of controller that make the system behave like some desired mechanical impedance (a mass-spring-damper for example). Students will recognize similarities between this impedance control law and the PD controller studied previously in Lab 5, and often times the two are interchangeable. The objective here is for our system to track some desired trajectory. It is accomplish by implementing an impedance control law that attaches a virtual spring and damper to a reference position of the actuator. Then, the control law cancels the system's natural dynamics and implements the desired mechanical impedance dynamics. Below is the command to run this part of the experiment.

```
roslaunch mtb_lab6_feedback_linearization impedance_control.launch
```

Students are advised to experiment with changing impedance control parameters and observe how the system responds.

2. P170 (Taurus) Testbed Labs

The P170 actuator is significantly more advanced than the basic Motor Testbed used in the previous labs (*Figure 15*). There are a few important things to remember when running the P170 testbed. *Warning: The P170 Testbed is a dangerous device.* If at any time it behaves in an unexpected manner, press the red "Emergency Stop" button. Keep hands out of pinch points such as near the hard stops. Always ensure that a reasonable Force Limit is set for the device (see below). Ensure that the P170 testbed is securely bolted to the table before using it. Be especially careful when loading the arm of the P170 testbed with heavy weights (it is not recommended to mount more than 10lbs on the load arm).

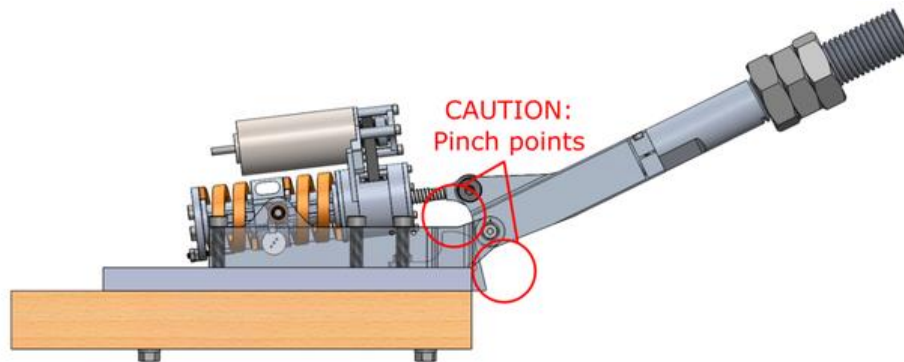


Figure 16. P170 Taurus Testbed

** Although the Lab experiments for the P170 Testbed have been developed, they are scheduled to be used in research projects in the spring 2018 semester.

The following labs have been developed:

Lab 1: Linkage position:

The purpose of this lab is to test the linkage equations that convert between actuator (linear) and joint (rotary) positions.

Lab 2: Linkage force:

The purpose of this lab is to test the linkage equations that convert between actuator force and joint torque.

Lab 3: Gravity compensation:

The purpose of this lab is to perform gravity-compensation, which will allow simpler controllers to work well even given a larger arm load.

Lab 4: Proportional Derivative Control:

The purpose of this lab is to control the position of the P170 Testbed actuator arm. The functionality of this lab is similar to that of MTB Labs 5, but with a heavier payload attached to the actuator arm.

3. Summary of the Most Important Results:

Huston Tillotson University was able to establish the Advanced Robotics Center (HT-ARC) that is the home of Robotics Lab. This lab was made possible through the grant award to acquire various equipment and instruments needed to design, experiment, and build robotics components, and to advance STEM education and research. In phase I of this grant, we furnished the Robotics Center with five (5) Actuator Testbeds each with a Control PC to simulate arm motion lifting (weight) control, and two (2) very powerful P170 (Taurus) Testbeds to simulate torso motion and control. We also established a lab for 3-D graphics design to model printable robotics components (shell) products with then print those components with the 3-D Printer. This lab also has five (5) computers each with 3-D software, and are networked through HP Server. Four (4) students enrolled in the course COSC4309 Computer Science Research/Project were the first cohort to be engaged in robotic research projects on the MTB Testbed at the Advanced Robotics Center.

The Phase II enabled us to contract the acquisition of Humanoid robotic test platform and associated tool kits and control computer. This system consists of multiple degrees of freedom for advanced robotics experimentation and control. This system will enhance and advance the knowledge gained in Phase I lab experiments. In an effort to further advance STEM Education and Research, the HT-ARC has established Modular Mobile Manipulator Robot lab that is used in the design, build Modular Mobile Manipulator Robots that can navigate obstacles while achieving its mission. The four (4) students who are currently enrolled in COSC4309 Computer Science Research/Project (fall 2017) were engaged in our robotics lab experiments on MTB Testbed, and will commence the assembly of a robotic arm to further their technical skills.

The awarded grant has made it possible to establish a computer science concentration in Robotics within the Computer Science Degree Program. The Robotics Program as designed has been approved by the Computer Science Department, and the School of Business and Technology (SBT). It is now awaiting approval of university Educational Program Committee (EPC).

Students (4) who are currently in COSC4309 are currently finalizing their experimental research observations and findings/results based on experiments on MTB Testbed for Poster submission to the South Central Region Consortium for Computing Sciences in Colleges conference. (<http://www.ccsc.org/southcentral/submissions/studentinfo.html>). The deadline for submission is before April 2, 2018.

The HT-ARC as part of the computer science robotic curriculum also has developed the following robotics courses leading to computer science degree with a concentration in Robotics:

- COSCxxxx: Introduction to Robotics
- COSCXXX: Fundamentals of Technical Additive 3-D Graphics
- COSC2328: Robotics Motivation and Building
- COSC2329: Robotics Mobility/Autonomous/Agents/Robotics Intelligent
- COSC2330: Human-Robotic Interaction
- COSC4327: Robotics System Project

Two of our Computer faculty members are active engaged in maintaining and supervising students' activities off class lecture hours as they perform their individual experiments. The students (4) who are currently in the COSC4309 have positive responses to teaching, learning, and the use of the MTB Testbed, and use of other experimental equipment in the lab. The success of this project has opened up another opportunity for the HT-ARC to engage in a grant subcontract award to research the Exo-Skeleton Ergonomics and Degree of Freedom Movement for Apptronik Systems Inc. This research will involve two CS faculty members, and two (2) CS students.

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Appendices

Tables:

Mode	Command Value	Meaning
MOTOR_CURRENT	(MOTOR, EFFORT)	Send desired motor currents to the embedded controller. Assume accurate current tracking is accomplished.
MOTOR_POSITION	(MOTOR, POSITION)	Send desired motor position to the embedded controller. A PID controller is implemented on the embedded controller to track motor position.
ACTUATOR_FORCE	(ACTUATOR, EFFORT)	Send desired actuator force to the embedded controller. A feedback controller is implemented on the embedded controller to track actuator force.
ACTUATOR_POSITION	(ACTUATOR, POSITION)	Not yet implemented.
ACTUATOR_VELOCITY	(ACTUATOR, VELOCITY)	Not yet implemented.
ACTUATOR_IMPEDANCE	(ACTUATOR, EFFORT) (ACTUATOR, POSITION) (ACTUATOR, VELOCITY)	Send desired actuator force, position, and velocity to the embedded controller. A PD controller's output is added to the actuator effort term and fed to an embedded force controller.

Table 1. Nomenclature: Control Mode Parameter set “Axon” Controller

Symbol	Description	Unit
wm	Motor velocity	rad/s
tm	Motor torque	Nm
im	Motor current	A
Vbus	Voltage of the power supply	V
Vm	Back-emf due to motor movement	V
N	Speed reduction ratio	N
h	Drivetrain efficiency	h
r	Motor winding resistance	
l	Motor winding inductance	Ω
kt	Motor torque constant	Nm/A
d	Mass distance from pivot	m
tgt	Ground truth torque	Nm

Table 2. Nomenclature 1. Symbols and units “Torque” Constant

Symbol	Description	Unit
w_m	Motor velocity rad	s
w_{mo}	Motor no-load velocity rad	s
k_w	Motor back-emf constant rad	s_v
V_{bus}	Voltage of the bower supply	V
r	Motor winding resistance	
l	Motor winding inductance H	
V_m	Back-emf due to motor movement	V

Table 3. Nomenclature 2. Symbols and units “Speed” Constant

Symbol	Description	Unit
Θ	Motor position	rad
$\dot{\Theta}$	Motor velocity	rad/s
t	Motor torque	Nm
i	Motor current	A
V_{bat}	Voltage of the battery / power supply	V
V_s	Back-emf due to motor movement	V
j	Motor inertia	$kg\ m^2$
b	Motor viscous friction	Nms/rad
r	Motor winding resistance	Ω
l	Motor winding inductance	H
k_t	Motor torque constant	Nm/A
k_v	Motor back-emf constant	rad/sV
i_c	Maximum continuous current	A
Θ_{max}	Maximum no-load velocity	rad/s
ω_0	Natural frequency of the open-loop velocity plant	rad/s
N	Transmission ratio (motor / output)	
Θ_d	Desired motor position	rad
$\dot{\Theta}_d$	Desired motor velocity	rad/s
$\ddot{\Theta}_d$	Desired motor acceleration	rad/s ²
$\tilde{\Theta}$	Motor position error	rad
$\tilde{\dot{\Theta}}$	Motor velocity error	rad/s
k_p	Proportional gain of PID controller	A/rad
k_d	Derivative gain of PID controller	A _s /rad
w_c	Cutoff frequency for PID controller's filter	rad/s
i_a	Inertial acceleration compensation term	A
i_{gc}	Gravity compensation term	A
g	Acceleration due to gravity	m/s ²
m	Mass of an unbalanced motor load	kg
ω_n	Natural frequency of a second-order system	rad/s
ζ	Damping ratio of a second-order system	
$\tau\{\}$	Laplace operator	
s	Complex frequency variable used in Laplace transforms	

Table 4. Nomenclature: Symbols and Units “Feedback” Linearization